Renewable and Sustainable Energy Reviews 69 (2017) 902–911

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A pressure-based method for monitoring leaks in a pipe distribution system: A Review

A. Abdulshaheed*, F. Mustapha, A. Ghavamian

Department of Aerospace Engineering, Universiti Putra Malaysia, Malaysia

ARTICLE INFO

Keywords:
Pipe leak
Pipe roughness
Flow condition
Unsteady friction factor
Pipeline distribution system

ABSTRACT

Leakage from a pipe network possibly poses significant environmental destruction and economic losses due to the release of potential energy. While the pipe network may be planned and constructed to satisfy the requirements of rigorous conditions, it is quite hard to avoid the subsequent appearance of leakages in a pipeline during the system's lifetime. Pressure leak detection enables a fast and reliable action response which is necessary to minimise the damage. Many leak detection approaches have been previously suggested. These methods basically depend on numerical modelling and transient analysis, such as inverse transient analysis, time domain analysis and frequency domain analysis, the negative pressure method, etc. Many methods build upon the analysis of the variation of measured pressure, such as the pressure residual vector method. Hydraulic leak detection has the important advantage of being less costly and has a faster response compared to other leak detection approaches. In this work, various leak detection methods based on pressure are listed and the analysis is reviewed. Both steady state and unsteady state conditions are discussed. The advantages and disadvantages of each approach are mentioned. In addition, methods are included that are suitable for use in both the oil and water industries.

1. Introduction

The detection of a leak in a pipe is the first line priority for many companies and governments. Millions of dollars have been dissipated due to the loss of fluid through pipe leaks [2]. Moreover, from the point of view of health concerns, there is a potential hazard of a contaminant infiltrating a water network system, due to an existing leak in the wall of a water network pipe [28]. Recently, a new challenge has been constructing new water reservoirs [33]. The power for pumping represented in the energy consumed by the distribution system is the master key in developing network energy efficiency as well as different physical and operational energy efficiency measures [3,47]. Water treatment and distribution have risen over the last two decades and this has accelerated the need for a better leak detection method. The American Water Work Association (AWWA) has recommended that the target for water losses in a water distribution system should be less than 10% [32]. Researchers have dedicated their research towards detecting and localising leakage. Leakage has been classified into two main types, namely rupture and background [22]. A rupture is a leak that occurs instantly due to an increase in flow over the maximum pipe capacity or because of excessive stress on the pipe wall. A background leak occurs gradually over time and is typically caused by the progress of corrosion or under a deteriorating situation. The second type is more difficult to detect because of the slow formation process with adequate low pressure decline. In contrast, a rupture occurs instantly with an obvious pressure reduction, which can be detected by pipe monitoring based on sensors. There are many methods available to detect and locate a leak, ranging from visual line walking checking, direct mechanical excavation to sophisticated model-based techniques. The main objective of this paper is to illustrate the most important parameters that affect the detection of pipe leakage from the available detection techniques. In addition, producing leak detection methods for pipe distribution based on application in different fields of industry will be explored. Moreover, the advantages of applying leak detection methods and field observations, as well as disadvantages of each method are compared to provide a clear picture of the possibilities of application in various industrial fields. The paper presented here concentrates on pressure detection methods under the different pumping conditions of steady state and unsteady state. Moreover, the conveyance and distribution of network pipe leak detection methods are discussed. Some of the methods that can be used for steady and unsteady flow conditions are shown in (Fig. 1).

To construct an effective and reliable pipe supply network, a model based on the hydraulic method has been used to establish a monitoring

* Corresponding author.
E-mail addresses: ali2007en@yahoo.com (A. Abdulshaheed), faizalms@upm.edu.my (F. Mustapha), aidin.gha@gmail.com (A. Ghavamian).

http://dx.doi.org/10.1016/j.rser.2016.08.024
Received 12 May 2015; Received in revised form 19 January 2016; Accepted 12 August 2016
1364-0321/

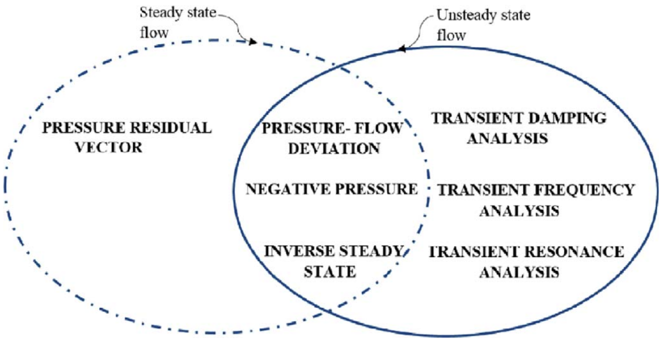

Fig. 1. : The relation between leak detection methods based on pressure measurement [51].

system. The data measured from the supply network was used for the boundary conditions. The hydraulic-based method is still under development because the leak detection technique is far from ideal for many reasons [58]. Furthermore, ground penetration radar and acoustic monitoring devices, as well as physical inspection, are available. However some of these techniques require isolating and temporarily shutting down part of the system that is to be investigated [12]. Techniques based on detecting and locating leaks from pressure monitoring devices allow more effective and less costly searches in situ [48].

2. Hydrostatic pressure testing method

Integrity need to be imposed on oil and gas pipelines, which are considered to carry hazardous fluid; hydrostatic pressure testing is applied to prevent the formation of leaks during normal operation conditions and to satisfy the safe operation of the work. The test is normally carried out after the construction of the pipeline or before the extension of the pipeline system, as well during normal operation. The hydrostatic pressure testing (non-flowing water), which uses pressurised water as a media, is generally used to investigate integrity after the pipeline system has been constructed [10]. The pipeline is normally tested by applying a pressure value of at least 125% of the maximum operation pressure for the duration of at least 4 h. In the case of an underground pipeline, an additional 4 h with the pressure value of 110% of the maximum operating pressure, is applied to the pipeline for satisfying integrity. A compressor can generate the pressure that is applied to the pipeline during the test. The spike test is applied as precautionary procedure to avoid the phenomenon of pressure reversal [23]. The spike test method prevents the growth of any crack during pressure reduction after the hydrostatic test, or as a result of the pressure operation cycle. If the pipe successfully passed the test, it means that the pipeline did not contain any defect leading to a fault in the pipeline system. These procedures are very important to the methods of pipe production that use low-frequency electric resistance welding (LFERW) and lap welding (LW). The pneumatic pressure test method is performed using compressed gas instead of water as a testing media. The pneumatic method is employed on a pipeline system that is working under a pressure of 100 psi to prevent system failure and increase system integrity.

3. Inverse transient analysis method

Inverse analysis has been commonly used in ground water and transport problems. The inverse transient method can be applied to a pipeline network, especially a water distribution network [21,43,52]. A water network can have a much more complex arrangement compared to a normal single oil or gas pipeline and the differences between the measurements and modelling are usually addressed by the tuning process. An inverse transient method (ITA) has been developed by applying a transient model based on the fact that an enormous amount of measurement data can be provided by a modern monitoring system [52]. By using this approach, it was *anti*cipated that having more measurement data could give a more precise calculation of the friction factor of the pipe, which in turn could lead to a better forecast of leaks; this could detect a 0.15% pipe leak over the cross sectional area in terms of both the location and the size of the leak. Pressure transducers were used for the acquisition of the measurement data [45]. The pipeline was examined using the generated model, which was based on the measurement data from the water hammer simulation. The transient method can be used for leak detection and location, in addition to system parameter calibration. An application of ITA for the pipeline was described by Nash and colleagues for a valve placed at the end of the pipeline which was used for transient generation, and again the measurement data was artificially generated by the transient model [34] as illustrated in (Fig. 2).

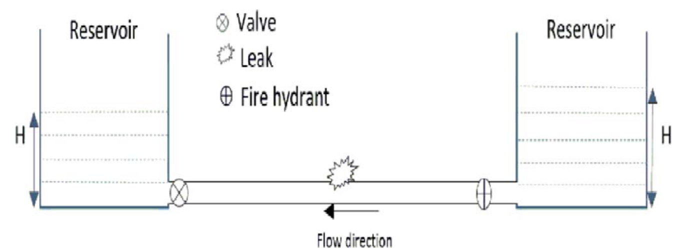

Fig. 2. : Inverse transient analysis method [33].

The most difficult problem encountered during the experimental work was the modelling of the transients in the pipeline system. There was a slight difference between the two cases, namely the modelled and the measured data, which resulted in a great difference between the values of the results. Normal transient models were far from satisfactory to be applied in the case of the inverse transient method compared to the measured transients. The major reason for these variances was located in the unsteady friction, with a two dimensional or three-dimension effect that had not been considered or properly considered by most transient models [7,47,55]. The presence of the friction factor in the distribution system inherently decreases the magnitude of the wave pressure that propagates during valve closure in the inverse transient analysis method. The friction value in all pipe systems depends on the square velocity of the fluid inside the distribution system. After the leak occurred, disturbance of the pressure began in the pipe system as it tried to establish new equilibrium [44]. The change in the friction factor value during the disturbance (water hammer) played a significant role in the pressure value estimation [40]. The relation between the friction factor and the parameter of the fluid transient wave is illustrated in the following equation [46]:

$$\frac{\partial v}{\partial t}+\frac{1}{\rho}\frac{\partial P}{\partial x}+v\frac{\partial v}{\partial x}+f\frac{v}{2D}/v/=0$$

where p,v,ρ,f , D are the pressure, velocity, fluid density, friction factor and pipe diameter respectively. The equation shows that the fraction factor value depends on the pressure of the fluid wave, the density of the fluid and the flow velocity [44,46]. The inverse transient model was verified in a straight single pipeline in the Robin Hydraulic Laboratory at Adelaide University [49]. [30] posited a solution to this insufficiency that employed the analysis steps of transient events. The minimisation approach was used to fit the measured data to the model by employing the ad joint Levenberg-Marquardt minimisation method, and later the genetic algorithm (GA) with new schemes was applied. The outcome of the procedure was satisfactory, but the applied GA, compared to the LM, was computationally unproductive. In general, the GA method takes a long time for objective function assessments as well as for its inner computation [24]. considered the problems and benefits of each mathematical and nature-based exceptional optimisation method and developed a novel solution procedure for ITA. They introduced a hybrid

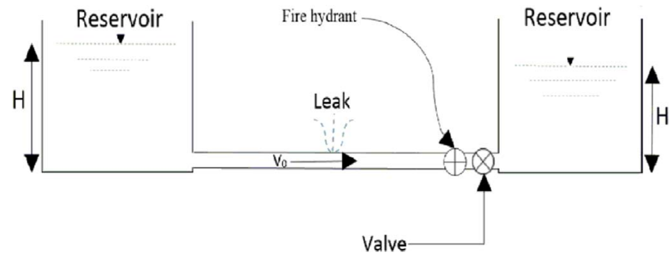

Fig. 3. : Back flow transient analysis method [22].

optimisation model consisting of the two formerly used methods of LM and GA to reduce the volume of computations as well as to obtain more reliable results using GA-LM scheme. The inverse transient method of [42] is a well-known approach for the leak detection and calibration of a pressurised pipe system. To overcome some of the main uncertainties in the inverse transient unsteady method, a novel time-domain approach for leak detection in a pressurised pipeline was developed. Most time-domain approaches are considered as a sub-category of inverse transient analysis. The applied approach model was free of the need for the accurate estimation of the valve specified. The new method was denoted as backward transient analysis (BTA) and was based on a measurement and numerical hydraulic method [22]. This is illustrated in (Fig. 3).

There are many unspecified parameters which influence the valve model manoeuvres in reality, such as unsteady friction losses, initial steady state conditions and collected transients. The valve, as the transient initiator, plays a substantial role in the whole leak recognition process. Therefore, omitting the uncertainties of the valve data from the transient numerical modelling calculation is the main target of the proposed method, as in (Fig. 4).

The backward transient analysis (BTA) models are a developed form of the method of characteristics (MOC), which is basically explained by [53]. They solve the hyperbolic partial differential equations in each node , since the initial condition and the valve description have been excluded from the modelling. In addition, pressure and wave computation can be started at any time after valve closure, when overlapping waves in the collected signal have disappeared. The leak occurring at characteristic nodes has an implied uncertainty in its location depending on the frequency. Thus, the sampling frequency should be set for the minimum requisite leak location uncertainties.

4. Transient steady state method

The transient steady state leak detection method is the first application of inverse transient analysis and has been popularly used in ground water conveyance problems based on the steady state pipe network model. The use of inverse steady state analysis to find a leak was carried out by [37]. The data consisted of flows and pressures from various positions in the network and the approach behind the analysis was to calibrate the parameters of the steady state equation and include a leak area at the nodes. Transient analysis methods are based on the properties of the transition and reflection of a pressure wave [5]. The momentum and energy equations are investigated and the friction loss is computed according to the quasi-static method, so the pressure values and flow recording can be used for a leak detection pipe system. Transient events can be caused by a quick closure of the end valve [6]. Leak detection is based on the difference between a pressure predicted by the hydraulic model and the real pipeline pressure. The leak is localised through investigating the time differences between the transient and the wave reflections from the leak [6]. One of the large obstacles in advancing these models is the state of the pipes, especially if they are old. It is very hard to obtain reliable estimates of the roughness as this phenomenon can drive the friction factor value to increase relatively with pipe age. From the unsteady pressure traces on

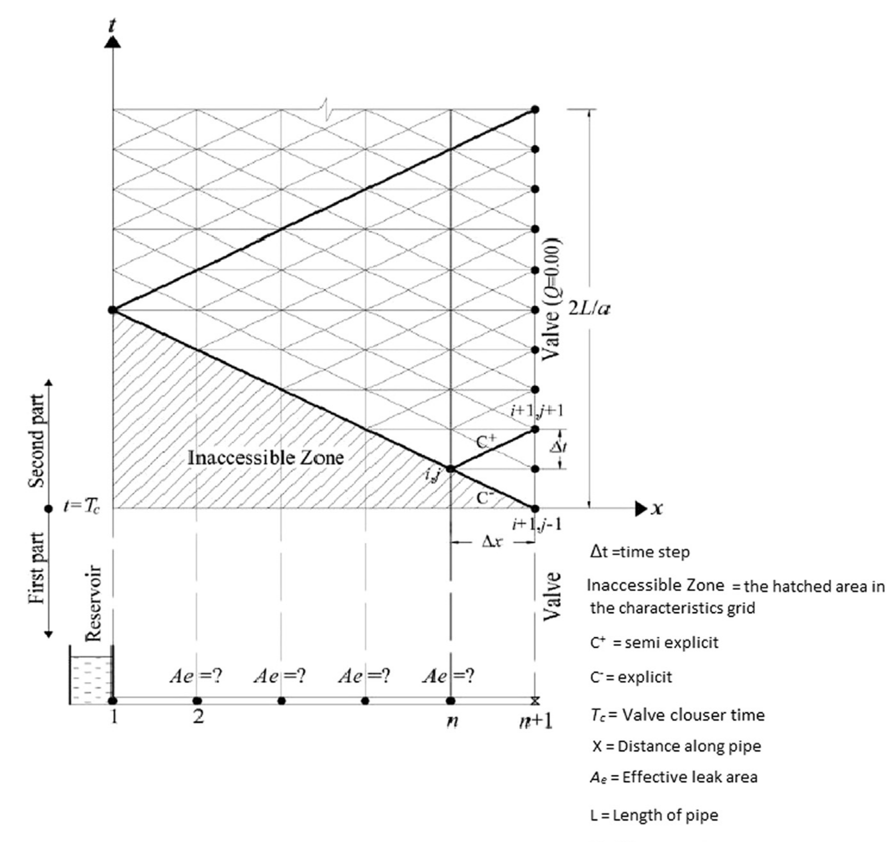

Fig. 4. : Back flow (finite difference) approach [22].

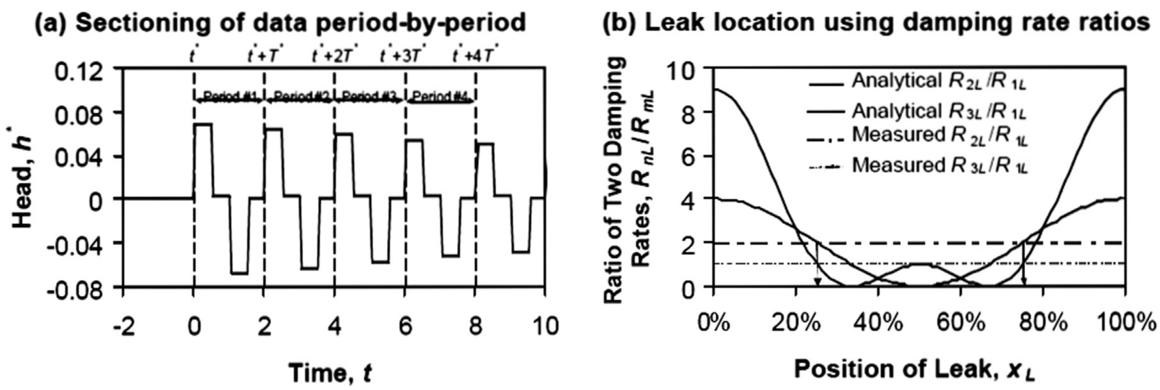

Fig. 5. : Transient damping method steps to detect and locate leakage [25].

a number of nodes in the network, the goals are to determine the location and magnitude of any leaks that are occurring and the friction factor for each pipe in the network [37]. introduced inverse steady state analysis that used sets of measured steady state pressure data at different model positions to both calibrate the pipe roughness and locate leaks in the pipe networks. A potential problem observed was the ability of their solution method to be applied in large water distribution networks [48].

5. Transient damping method

The inverse transient approach requires accurate information about the boundary conditions and transient generation details for use in modelling. This can complicate the implementation of the inverse transient method. An alternative idea is to use the information from the more easily measurable properties of the transients for leak detection. One such property is the damping behaviour of the transients at the time when the leak occurred. Because the transient flow in the pipeline is approximately linear, the solution of the equation, which is conducted with respect to the estimation of the pressure value, can be expressed in the scope of a Fourier series. Friction loss is assumed to be constant during a transient event in the case of steady state flow. While empirically, the value of the friction loss is more than previously estimated in case of unsteady state flow. Dissipation in the pressure values had been noticed, and is practically caused by increasing the friction loss value. However, the error in the estimation of the pressure model value compared to the measured pressure value normally indicates an incorrect estimation of the friction factor [9] as in the following equation [9]:

$$\frac{\partial Q}{\partial x}+gA\frac{\partial H}{\partial x}+\frac{f}{2DA}Q/Q/=0$$

From the study conducted to analyse the friction loss related to the wave transient, which was generated by the valve closure, the damping of the friction without any evidence of the existence of leaks is noted to be exactly exponential, while the damping behaviour in the pipeline containing the leak is approximately exponential. Leaks are identified in the inverse damping method by isolating the anomalous pressure value. The fault presence in the pipeline system caused an increase in the damping rate of the transient signal [28]. The rate of damping of the leak is subject to different factors such as the leakage characteristics, the pressure value inside the pipeline, the location of the transient generation point, and the shape of the transient damping. The particular frequency components of the pressure wave signal are damped faster than other wave parameters. The pipe's physical elements, such as joints, hydrants and valves, cause transient damping. Thus, friction is not the only source of transient damping. Furthermore, the representation of all the physical factors in the pipeline system is considered essential for optimum damping [36]. The flow attenuates the transients over time, returning to equilibrium conditions when a leak is present. A mathematical model has shown that the leak exponentially damps each Fourier component of the pressure wave signal differently. The wave damping rate (RNL) caused by leakage for then^{th}component is given by [54]:

$$RNL=\frac{C_d A}{A}\frac{a}{\sqrt{2gH_{L0}}}sin^2(n\pi x_l)$$

The ratio of any two damping rates gives an appearance of the leak location that is independent of the leak size. Therefore, leaks may be detected and located using such a ratio [54].

$$\frac{\mathrm{RNL2}}{\mathrm{RNL1}}=\frac{sin^2(\mathrm{n_2\pi x_L})}{\sin^2(\mathrm{n_1\pi x_l})}$$

A transient was generated in a pipeline and the pressure response was measured. The first two Fourier components would be sufficient to locate the leak as shown in (Fig. 5).

6. Inverse resonance method

The existence of a leak in a pipeline produces cause-dependent behaviour in the flows and pressure during a transient event. For this type of behaviour it is better to perform analysis in the frequency-domain. Therefore, one idea for a leak detection method may be based on how the pressure in a leaking pipeline responds to different frequency disturbances when the leak is present, as shown in (Fig. 6).

A pipeline system can be represented by an input, such as a valve movement, an output such as the measured pressure, and a mathematical operator that relates the input to the output for water transients that are small compared to the static condition. The system is approximately linear. The entire linearisation used in this analysis includes a linear approximation of the leak discharge $Q = C_d A_l \sqrt{2gh}$ as the function of the head and the linearisation of the valve discharge. These are equations characterised in the form of normal differential equations and can be solved by the separation of variables. Basically, there are two methods for solving oscillating flow in the pipeline and pipe networks, namely the impedance method [55] and the transfer matrix method [30]. The transfer matrix method is easy to apply to a complex pipe system, since the results can be verified numerically using the method of characteristics (MOC) with non-linear equations in order to determine the scope of the response to sinusoidal valve fluctuations. After the resulting pressure fluctuation has settled down to a steady oscillation, the amplitude of the pressure oscillation is determined using the Fourier decomposition of the signal. An inverse resonance technique is similar to the inverse transient method of [31] and is easy to apply in a complex pipeline system. For a pipeline system with a periodic excitation due to pressure fluctuations, the steady-oscillation flow equation represents a linear system. Accordingly, the system response for a number of different frequency excitations can be accumulative by the sum of the response of each system component as shown in (Fig. 7). The frequency range has been scaled, where one

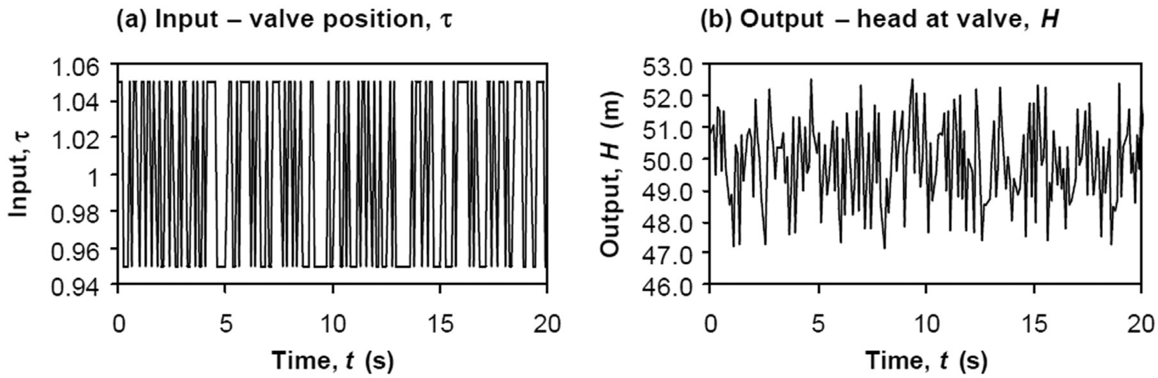

Fig. 6. : Input and output for a pipeline system [25].

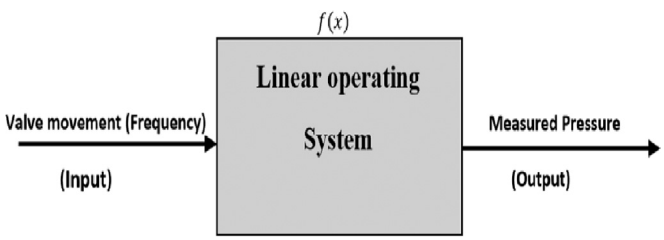

Fig. 7. : Input and output representation of a pipeline system [25].

frequency is tested at a time and it is also slow and inefficient [27]. An applicable solution is to use pseudo-random binary signals (PRBS) to generate steady-oscillatory conditions.

The linear operator defines the system response to different frequency inputs and is sometimes called a transfer function. The transfer function can be used to find leaks over a wide band of frequencies and may be inputted using a pseudo-random binary signal (PRBS) which determines the transfer function for all frequencies at once, rather than having to perform a frequency-sweep [29]. A leak causes a variable effect on the system transfer function depending on the size and location of the leak. The pipeline is excited by a PRBS using an oscillating valve device, a displacement meter measures the system input, while a pressure transducer measures the system output. The peaks in the transfer function correspond to the resonant frequencies of the pipeline.

7. Pressure-flow deviation method

The pressure-flow deviation method is largely used in model-based leak detection programs in combination with a mass balance approach to cover full-time leak detection for a vast range of operating conditions. Pressure-flow deviation methods are basically a subset of the inverse transient leak technique. The first applied field of the inverse transient analysis method was the wide use in ground water transport problems based on a steady state pipe network model. The governance model for the pressure-flow deviation method is that the calculated pressure and flow are based on either steady state models or transient flow models and should be equal to the measured value, if possible, of the leak in the pipeline. A leak can be declared if there are deviations between the two pipe edges. When the leak develops, the flow upstream of the leak is increased, causing a large pressure drop. Downstream of the leak, the flow remains the same as that seen by the downstream model and the pressure gradient remains unchanged. The results indicate a deviation between the modelled and measured pressure at the downstream end of the pipeline. Due to the quick response time, the majority of the pressure-flow deviation methods applied in leak detection systems are based on the transient analysis model [14]. Measured values, normally the upstream flow or pressure and downstream value pressure or (flow) from a supervisory control and data acquisition SCADA system, are used as the surrounding conditions for transient modelling analysis. The predicted pressures and flows are compared with the measured values at the upstream end, the downstream end or any other location along the pipeline. In reality, the calculated values are rarely equal to the measured values even when there is no leak in the pipelines. This is because of the errors in the measurements and approximated element values of the pipelines that are used in the mathematical model, such as the density of the fluid, the roughness and diameter of the pipe wall and unsteady friction. Therefore, a calibration process is needed that is conducted in a pipeline during the no-leak period. The sensitivity of the pressure-flow deviation method is usually in the order of minutes subject to the leak being a detectable size, the accuracy of the measured values and the modelling. For a leak discharge of 5% of the total flow, the response time was in the range of five minutes or slower and the location error was about 33%. For a 10% leak discharge, the location error was about 22%. The pressure-flow deviation method is applied in the field of the energy industry; using this method in the oil and gas industry is applicable and useful. The real-time transient method (RTTM) can be employed during the startup of the gas pipeline system, where great compressibility results in a strong transient. The pressure gradient method is employed to Localise the pipeline system leak as in (Fig. 8). The leak detection system (LDS) does not have a universal parameter value that can be used in all oil or gas pipeline systems [41]. Each case should be investigated separately to suggest a suitable solution. In addition, another method (statistical pattern recognition) is employed widely with different pipeline leak detection methods, working as a means of leaks classification. The principle of working as a classifier implies the use of a threshold concept to identify the leakage. Pressure values are collected by the pressure transducer, implemented in different positions in the pipeline system. The pressure values inside the pipeline are compared with the threshold pressure value. The comparison procedure tries to determine whether the resulting pressure values are the same as the old values. Is there any significant change in the values that have been compared? The pressure values are tested using the Sequential Probability Ratio Method (SPRT) [41]. Leak detection depends on data driven which does not use the simulation model. It simply relays the statistical analysis of the data that was collected under the condition of the steady flow case [57]. A comparison was made between internal leak detection methods based on pressure value, with the detection method based on the compensated volume balance as shown in the (Table 1). The comparison in Table 1 shows that the pressure based method only can localise the leak in the distribution network. The high rate of the sensitivity option make the pressure methods favorites in the industrial application. Furthermore, the cost of the system item is lower than the method that depend upon flow meter which by implementing few sensors can monitor large piping zone area Table 2.

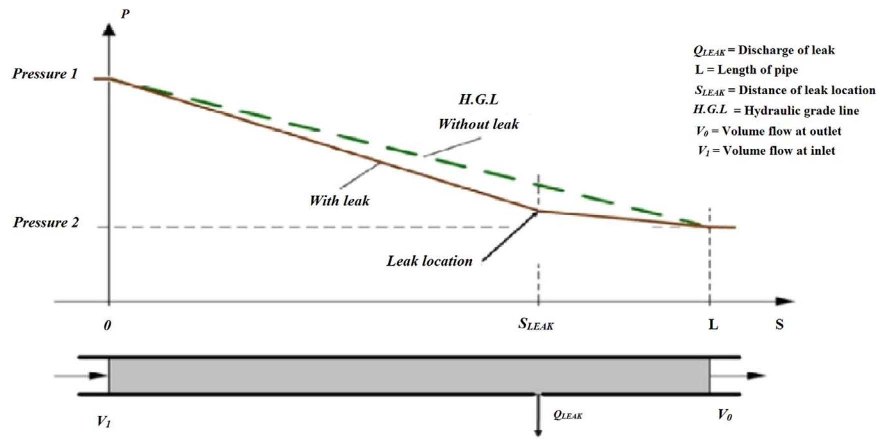

Fig. 8. : Gradient intersection method to detect and locate a leak [15].

8. Negative pressure wave method

The negative pressure wave method exploits the principle of acoustics [56]. The so-called pressure wave refers to the sound wave spent through the pipeline inner flow [11,23]. This is referred to as 'acoustic' since it is contingent on capturing and analysing a pressure wave travelling at the speed of sound. When a leak is present in a pipeline, the pressure is different between the inside and outside of the pipeline in the location of the leakage because the liquid quickly runs out of the pipe. The negative approach is obviously a pressure- based method and must not be confused with sonic / ultrasonic detection methods. As the initial pressure drop caused by a leak is instantaneous and short lived, it is necessary to record the pressure data quickly. Although the oldest negative pressure wave system has been available since the early 1980 s, it has not been widely applied due to the high false alarm rate caused by the old algorithm based on the bandwidth and the old hardware limitations. The detection system compares the real pressure from the pipeline with the estimated pressure from models under the same medium condition. The models are normally subjected to the momentum conservation equation and the energy conservation equations. Recently, a new sensor technology has enhanced the collection of pressure data at high frequencies (60 Hz). The model parameters will be tuned automatically using an optimisation method, as proposed by Levenberg and Marquard. The goal of the optimisation is to minimise the difference between the measured and the simulated variables. Due to practical testing considerations, three operational steps must be identified in normal operation. These are steady state, normal operation with small transients and start up with severe transients [16,41]. A sudden leak immediately propagates negative pressure at the speed of sound up and downstream through the pipeline. Such a wave can be recognised using a pressure transducer. It is also possible to calculate the location of a leak by timing the arrival of the pressure wave at two or more points in the pipeline. One pressure sensor is approved for leak detection only. Two transducers are the minimum number required for localising a leak in a pipe. In another case, the selected transmitters must be capable of detecting instant changes in pressure. The negative pressure wave method is able to detect leaks under steady state conditions, and small variations in pressure can possibly produce false alarms. The negative pressure wave approach is definitely useful in pipelines carrying liquids, but the energy of the pressure wave is spent during long flow pumping in gas pipelines. The concept of a detection and localisation method based on pressure drop in a leak free pipeline (pressure gradient method) is linear as shown in Fig. 8. The leak position can be determined, if the moment t_{down} (downstream) and t_{up} (upstream), when the $\Delta t = t_{down} - t_{up}$ [15]

$$S\text{leak} = \frac{1}{2}.(L - c.\Delta t)$$

If a leak occurs, the pressure profile develops a kink at the leak point as shown by the brown line in (Fig. 8), while the hydraulic gradient line is represented by a straight line between two points in normal conditions as shown by the green line in (Fig. 8). The leak location can be found by calculating the intersection point of the pressure profiles upstream and downstream of the leak. The classic gradient intersection approach computes the gradient of both lines using two pressure readings near the outlet [15]. [13] conducted a pressure gradient method for the analysis of losses in both a compressed air distribution system and a steam distribution system. The air compressed system is divided into three main segments: a generation system, distribution and end use. The main fact that made the detection of pipe leakage a difficult duty is the transparency characteristic of air. The loss of the leak in the field of industrial application is found to be 5%. The leakage discharge through a hole is in direct proportion with the pressure inside the pipe and the square radius value of the leak hole. Furthermore, the methods that are used to detect a leak from the steam distribution system normally depend on the measured pressure variation, fluid flow and mass balance. The application of the method of air leak detection requires the use of both statistical and computational models as a layer recognition of the leak position. Because of the dependency on pressure and flow parameters, determining the flow status as a factor of the Reynolds number can affect the monitoring of the pipe distribution system. Flow losses can be calculated by the Darcy-Weisbach equation. The friction factor value has been deduced from the Moody diagram where the value of the friction factor is relative to the roughness value and the steam temperature.

9. Pressure residual vector method

The residual vector method permanently monitors the pressure variation in a water distribution system. The method of leak detection and pre-localisation is the subject of improvement in a project carried out by Aguas Barcelona, the water technological Centre CETaqua, and the technical university of Catalonia (UPC) [26]. The residual vector method is a technique to advance and apply an effective system in order to identify precisely the leakage in a water distribution network. It applies an integrated approach and technologies that are attainable in usage by the water industry [35]. A huge amount of data will be obtained by using pressure and flow sensors inside the water distribution network. The residual method was developed to overcome the behaviour and complexity of the water distribution system with pressure demand. The application validation has been approved for

Table 1
Comparison of leak detection methods internal system (pressure based method and compensated volume balance method).

Selection Criteria	Compensated Volume Balance	Pressure Flow/Mass Balance Monitoring	RTTM	Negative Pressure Wave
SENSTIVITY	1% of nominal flow rate Rating: 5 (Very High)	3% of nominal flow rate Rating: 3 (Average)	1% of nominal flow rate Rating: 5 (Very High)	1% of nominal flow rate Rating: 5 (Very High)
Accuracy	± 2–3% of flow rate Rating: 5 (Very High)	± 2–4% of flow rate Rating: 4 (High)	± 2–3% of flow rate Rating: 5 (Very High)	± 1–4% of flow rate Rating: 4 (High)
Reliability (False Alarm Declaration)	Free of nuisance alarm depending on total accuracy Rating: 5 (Very High)	Free of nuisance alarm for compensation Rating: 4 (High)	Possible false alarm Rating: 3 (Average)	Free of nuisance alarm with filtering technique to remove noise Rating: 5 (Very High)
Robustness (Loss of Signal)	Depending on the Flow meter robustness and accuracy Rating: 4 (High)	Yes, not depending on the flow meter. Rating: 5 (Very High)	Depending on the Flow meter , temperature and pressure robustness and accuracy Rating: 3 (Average)	Yes, not depending on the flow meter Rating: 5 (Very High)
Leak Location Estimate/Accuracy	No Rating: 0 (None)	Yes Rating: 3 (Average)	Yes/1% – 2% of Pipeline Length Rating: 5 (Very High)	Yes/Within 100 m Rating: 3 (Average)
Cost (CAPEX and OPEX)	Approximately USD200K (Cost only on the hardware and software. Field instruments, engineering and installation are not included) Rating: 2 (Low)	Approximately USD 440 K (Price includes the hardware, software, 4 units of PT, 4 units of Flow meters, installation cost is excluded) Rating: 1 (Very Low)	Approximately USD 250 K (Cost only on the software and hardware. Field instruments, engineering and installation are not included) Rating: 1 (Very Low)	Approximately USD 280 K (price includes hardware, software and engineering Rating: 1 (Very Low)
Leak Size Detection	Yes Rating: 3 (Average)	Yes Rating: 3 (Average)	Yes/Less than 1 l loss Rating: 5 (Very High)	Yes/ 5 l loss Rating: 4 (High)
Response Time	Within 60 min Rating: 3 (Average)	From 5 min Rating: 5 (Very High)	Within 9 min Rating: 5 (Very High)	Within 60 min Rating: 3 (Average)
Complexity/Ease of use	Software is complicated, require training Instrument Required: Flow meter, Pressure, Temperature transmitter Rating: 3 (Average)	Software is complicated, require training Instrument Required: Pressure Transmitter Rating: 4 (High)	Software is complicated, require training Instrument Required: Flow meter, Pressure, Temperature transmitter Rating: 3 (Average)	Software is complicated, require training Instrument Required: Pressure Transmitter Rating: 4 (High)
Maintainability	Yearly calibration on the field instruments Rating: 4 (High)	Yearly calibration on the field instruments but more difficult Rating: 3 (Average)	Yearly calibration on the field instruments Rating: 4 (High)	Yearly calibration on the field instruments Rating: 4 (High)
Maintenance Support	Yes Rating: 5 (Very High)	Yes Rating: 5 (Very High)	Yes Rating: 5 (Very High)	Yes Rating: 5 (Very High)
application in the industry field	Oil and water	Oil and water	Gas and Oil	Hot gas, oil and water steam, compressed air, water distribution system

water pipelines and water distribution networks. The application of the pressure and flow sensors is considered an essential monitoring tool. In addition, the monitoring system uses sensors and mathematical models to determine any irregular pressure values and to inspect a fault location [4]. The sensors collect real pressure values in order to compare them with the results of the hydraulic model to detect any suspicious pressure variation. A simulation model has to be calibrated in order that the result gives a reliable description of the real working conditions [50]. Although a variety of factors may cause a discrepancy between the estimated and measured values, one stands out prominently, i.e. a leak. With the approximate knowledge of the input data, the data produced is mainly design parameters such as pipe, diameter, length and roughness, and operational parameters, such as nodal demands, real pressure and pump condition. Most of the uncertain input parameters are pipe roughness and nodal demand [19]. For experimental preparation, the water distribution network (WDN) should be divided into many parts, e.g. District Metering Areas (DMA) to minimise the number of sensors and to determine the water consumption [32,38]. In addition, the pressure monitoring methods concentrate on using pressure variation value analysis, which is measured through installing sensors inside the (DMA). The pressure variation can be analysed using residuals in which the differences in the sensor measured values and their hydraulic model estimations are analysed [39]. The first model was proposed for a pipe network by Bhave utilising pressure-driven demand to identify the minimum nodal demand that was required for the standard condition [1]. In addition, [17] assumed pressure-dependent demand and leakage in terms of water distribution network models and Chandapillai suggested a similar head-based scheme for a model for an uncontrolled outlet [8]. Wagner and colleagues proposed a generic pressure-driven demand method to control an outlet [49]. The global gradient algorithm (GGA) was used to develop EPANET2. Nowadays, the model that is commonly used in modelling a distribution network is the same as the model that is used in the EPANET program [20] as illustrated in (Fig. 9).

The investigation of the behaviour of the WDN is very important to produce accurate values for the parameters on which the hydraulic model depends. The behaviour can be determined by extracting the

Table 2
of symbols.

	Symbol	Scientific name	unit
1	ITA	Inverse transient analysis	–
2	GA	Genetic Algorithm	–
3	LM	Levenberg-Marquardt	–
4	BTA	Backward Transient Analysis	–
5	MOC	Method of characteristics	–
6	RNL	Wave Damping Rate	–
7	a	Wave Speed	m/s
8	C_d	Emitter Coefficient	–
9	A_L	Leak Area	mm^2
10	A	Pipe cross-sectional area	m^2
11	g	Gravitational Acceleration	–
12	H_L	Head at Leak	m
13	X_L	Dimensionless leak position	–
14	S_{leak}	Leak position	–
15	L	Pipeline distance	m
16	C	Speed of sound	m/s
17	Δt	Time difference between upstream and downstream	s
18	v	velocity of wave transient	m/s
19	p	Pressure of wave transient	m
20	f	Friction factor	–
21	D	Pipe diameter	mm
22	ρ	Fluid density	Kg/m^3
23	RTTM	Real time transient method	–
24	LFERW	Low-frequency electric resistance welding	–
25	LW	Lap welding	–
26	Q	Discharge	–
27	H	Pressure head	m
28	SPRT	Sequential Probability Ratio Method	–

properties of the network at different periods throughout the maximum and minimum water consumption period, e.g. the Minimum Night Flow (MNF). This allows the simulation of the hydraulic model and the pressure sensitivity analysis of the nodes in a network when a leak is present in a node. Simulation of the network via EPANET in the presence and absence of a leak provides an approximation of this sensitivity. The sensitivity of the matrices is considered as a threshold to detect leaks [18,43]. Silva and colleagues used a learning machine that could perform binary classification and pattern recognition as a support vector machine (SVM) for the task of real value function approximation (regression estimation) [42]. SVM are related to and can be considered to be a type of neural network. In this method, the simulation procedure passes the data through the EPANET program and the data is then passed to the SVM to predict the position and size of the leak. The EPANET driving program is used to generate data representing the pressure at the different nodes. The producing emitter coefficient has a convergence pressure effect in the EPANET program. The output data can be used as a training data set for SVM analysis. The analysis indicates that the prediction of the exact location has a 35% success rate.

10. Discussion and Conclusion

The pressure detection technique is considerably more sensitive than the other approaches to leak detection which have been invented for oil and gas pipelines, and the method can be used for water distribution systems. The detection system for pipe leakage is considered as the first line of systematic defence when fast detection and high sensitivity is required. In the context of the fact that high

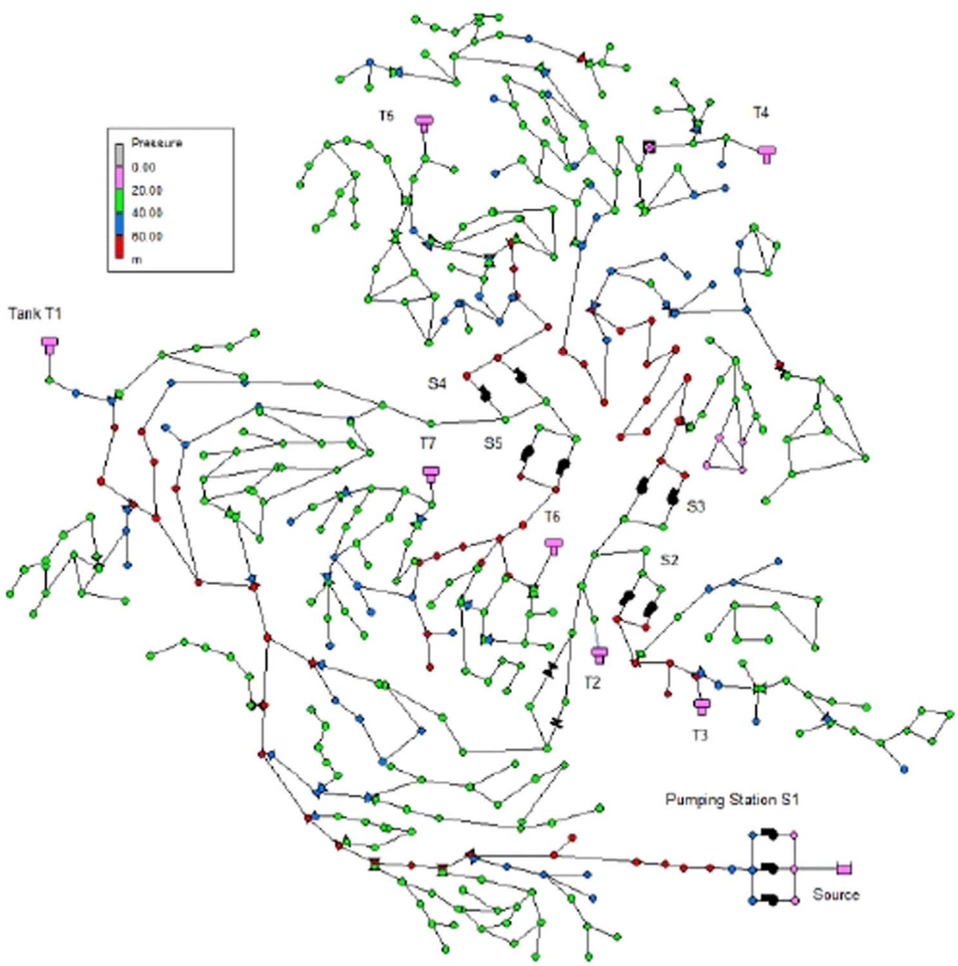

Fig. 9. : Analysis of pressure and simulation of a pipe leak in the EPANET program [43].

sensitivity inherently produces a high rate of false alarm, more than one leak detection method is employed in the same system in order to reduce the consequences of system false alarm and produce a reliable system that is able to interpret the changes in the transient properties for the flow piping system. The negative pressure method may not be able to identify a leak induced in limited cases, depending on the location of the transient measurement. Moreover, the (RTTM) model is applied in the oil and gas industry, and the model is able to simulate all of the dynamic fluid characteristics (flow, pressure, and temperature) as well as the fluid characteristics (density, viscosity), which are very important in the oil and thermal industries in order to overcome the properties of compressed fluid when the viscosity and density inherently change relative to the fluid temperature. Most of these techniques are not suitable because of the highly complex topology and customer consumption inherent in a water distribution system. Moreover, all of the transient analysis methods are only suitable for pipelines, where closed system conditions are required. In contrast, the approach of monitoring pressure variations is suitable for a water distribution network with nodal demand (customer consumption) and a pipeline system. The EPANET program is especially applied in the water distribution networks. Customer demand is the main factor through which distribution of the fluid flow in the pipe network model is controlled. This means representing the way that people consume water during the peak demand period or minimum night flow (MNF), while all of the previous models have failed to represent such important parameters. Calibration of the network model is an essential procedure for reducing the uncertainties of the network parameters. Friction loss is calculated in the steady state flow condition with three case equation (Darcy-Weisbach, Hazen-Williams, Chezy-Manning). The decision behind using each of these equations is subject to the properties of the pipe distribution network and the fluid characteristics. The huge difference is avoided by estimating the friction factor in a steady state condition. In contrast, the friction factor value increases in the inverse transient detection methods; this is caused by the fluid wave speed and the liquid viscosity (in the case of compressible fluid). The analytical transient flow calculation is not a trivial matter in a real network due to the wide range of non-linear systems of equations that describe the dynamic behaviour. Since it is not based on the transient analysis of pressure waves, the leakage identifying procedure is performed by comparing the transient pressure value data with the estimated value using the output of the network mathematical model. Generally, the model-based method stands on the hydraulic model using system measurements which have been built at the development stage as boundary conditions. The performance of the system based on a model-based leak detection technique is so far the best choice available. The inverse damping method is used to obtain the pressure damping values in order to detect anomalous system behaviour, while the inverse resonance method is used to detect the disturbance of fluid flow and the properties of the system as a function which produces the pressure value of the transient wave. This allows the identification of the influence of all the pipeline properties on the wave pressure impulse. In summary, the pressure based method only can localise the leak in the distribution network. The high rate of the sensitivity option make the pressure methods favorites in the industrial application. Furthermore, the cost of the system item is lower than the method that depend upon flow meter which by implementing few sensors can monitor large piping zone area.

Acknowledgement

Thanks to Dr. Joacum Sausa for support special thanks to UPM University for providing and supporting all the research requirements.

References

[1] Bhave PR. Node flow analysis distribution systems. Transportation. Transp. Eng. J. 1981;107(*4*):*457*–67, p.16401.
[2] Black P. A review of pipeline leak detection technology. Pipeline Syst. Springe. Neth. 1992:287–98.
[3] Bolognesi A, et al. Energy efficiency optimization in water distribution systems. Procedia Eng. 2014;70:181–90.
[4] Brdys MA, Ulanicki B. Operational control of water systems: structures, algorithms, and applications. Automatica 1994;11(32):1619–20.
[5] Brunone B. Transient test-based technique for leak detection in outfall pipes. J. Water Resour. Plan. Manag. 1999;125(5):302–6.
[6] B., Brunone, M., Ferrante and L., Ubertini, 2000. Leak analysis in pipes using transients..... *Journal of Hydro. Engineering*.
[7] Brunone B, Golia UM, Greco M. Effects of two-dimensional on pipe transients modeling. Int. J. Multiph. Flow. 1996;22(1001), pp.131–131.
[8] Chandapillai1 J. REALISTIC SIMULATION O F W A T E R DISTRIBUTION SYSTEM. J. Transp. Eng. 1991;117(*2*):*258*–63, 117(2), pp.258–263.
[9] Duan H, et al. Essential system response information for transient-based leak detection methods. J. Hydraul. Res. 2010;1686(December).
[10] Edwards, M., 2014. Pipeline Hydrostatic Pressure Test Pass/Fail Criteria Used by a Regulatory Agency. In 2014 10th International Pipeline Conference (pp. V004T13A001-V004T13A001). American Society of Mechanical Engineers.
[11] Er Li, Y. fan and X.L., 2010. negative principle localization.pdf. *jornal of applied sciences issn 1812–5654*.
[12] Farley, M. and Trow, S. eds, 2003. Losses in water distribution networks: a practitioner's guide to assessment, monitoring and control. *IWA Publishing*.
[13] Fortes MZ, Brandão GP, Dias BH, Albuquerque CJ. SOFTWARE SUPPORT FOR THE EVALUATION OF ENERGY LOSSES FROM LEAKS. Potentials, IEEE 2014;33(2):26–31.
[14] Fukushima K, Maeshima R, Kinoshita A, Shiraishi H, Koshijima I. Gas pipeline leak detection system using the online simulation method. Computers. Comput. Chem. Eng. 2000;24(2):453–6.
[15] Geiger, I., 2005. Principles of leak detection. Fundamentals of leak detection. KROHNE oil and gas. Available at: http://ma.krohne.com/fileadmin/files-2/PipePatrol/KROHNE_Gerhard_Geiger_Principles_of_Leak_Detection_2012.pdf [Accessed February 23, 2015].
[16] Geiger, G., Matko, D. and Werner, T., 2003. Extending classical pipeline models with Neural Nets. *In Proceedings of the 11th Mediterranean Conference on Control and Automation*.
[17] Germanopoulos G. A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models. Civ. Eng. Syst. 1985;2(3):171–9.
[18] Gertler J. Fault detection and diagnosis in engineering systems. CRC press,; 1998.
[19] R.G., Giovanni de Marinis & A.L., 2005. INVERSE PROBLEMS IN HYDRAULIC NETWORK MODELLING PARAMETER IDENTIFICATION IN A REAL CASE STUDY. *www.researchgate.com*.
[20] Giustolisi O, Savic D, Kapelan Z. Pressure-Driven Demand and Leakage Simulation for Water Distribution Networks. J. Hydraul. Eng. 2008;134(5):626–35, (Available at): http://ascelibrary.org/doi/abs/10.1061/%28ASCE%290733–9429%282008%29134%3A5%28626%29.
[21] Haghighi A, Ramos HM. Detection of Leakage Freshwater and Friction Factor Calibration in Drinking Networks Using Central Force Optimization. Water Resour. Manag. 2012;26(8):2347–63.
[22] Haghighi A, Covas D, Ramos H. Direct backward transient analysis for leak detection in pressurized pipelines: from theory to real application. J. Water Supply.: Res. Technol. 2012;16(3):189–200.
[23] Journal (pipe technologies & services LLC) (http://www.pipetechs.com/operating_principle.html)
[24] Kapelan ZS, Savic DA, Walters GA. A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. J. Hydraul. Res. 2003;41(5):481–92.
[25] M., Lambert, A., Simpson, J., Vtkovsk, X.J., Wang and P., Lee, 2003. A Review of Leading-edge Leak Detection Techniques for Water Distribution Systems. *awa convention australia*.
[26] Landeros E., Pérez R., Peralta A., C.G., 2009. Leakage detection using pressure sensors and mathematical models. *Water Loss 2009, Cape Town, South Africa*.
[27] Lee PJ, Tang VM, Kuo YL, Y HJ. Analysis of Leaks in Pipeline Systems Using Coded Transients. *Australia*: Dept. of Civil & Environmental Engineering, Adelaide University,; 2000.
[28] Lee PJ, Duan HF, Tuck J, Ghidaoui M. Numerical and Experimental Study on the Effect of Signal Bandwidth on Pipe Assessment Using Fluid Transients. AMERICAN SOCIETY CIVIL ENGINEERS 2014;141(2):1–10.
[29] Lee PJ, Vítkovský JP, Lambert MF, Simpson AR, Liggett JA. leak detection in pipelines using an inverse resonance method. *Reston, Va*: ASCE,; 2002. p. 1–10.
[30] Liggett J a, Chen L-C. Closure to "Inverse Transient Analysis in Pipe Networks" by James A. Liggett and Li-Chung Chen. J. Hydraul. Eng. 1996;122(8):288.
[31] Liggett JA, Chen LC. Inverse transient analysis in pipe networks. J. Hydraul. Eng. 1994;120(8):934–55.
[32] Macdonald, G. & Yates, C.D., 2005. DMA Design and Implementation , a North American Context. In *Leakage 2005*. pp. 1–8.
[33] Maliva R, Missimer T. Domestic and Agricultural Water Conservation. In Arid Lands Water Evaluation and Management. Springer Berlin Heidelberg,; 2012. p. 669–97.
[34] Nash1 GA, Bryan W Karney. EFFICIENT INVERSE TRANSIENT ANALYSIS IN SERIES PIPE SYSTEMS. J. Hydraul. Eng. 1999;761–764(July):761–4.
[35] Pérez R, Puig V, Pascual J, Quevedo J, Landeros E, Peralta A. Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. Control Eng. Pract. 2011;19(10):1157–67.

[36] Puust R, Kapelan Z, Savic DA, Koppel T. A review of methods for leakage management in pipe networks. Urban Water J. 2010;7:25–45.
[37] Ramos H, et al. Surge damping analysis in pipe systems: modelling and experiments. J. Hydraul. Res. 2004;42(March 2015):413–25.
[38] D., Rogers & A., Bettin, 2012. *Saving the World ' s Most Precious Resource*, INTECH Open Access Publishe.
[39] Perez R, Sanz G, Puig V, Quevedo J, Cuguero Escofet MA, Nejjari F, Meseguer J, Cembrano G, Mirats Tur JM, Sarrate R. Leak Localization in Water Networks: A Model-Based Methodology Using Pressure Sensors Applied to a Real Network in Barcelona [Applications of Control]. Control Syst., IEEE 2014;34(*4*):*24*–36, (august).
[40] Shamloo H, Haghighi A. Optimum leak detection and calibration of pipe networks by inverse transient analysis. J. Hydraul. Res. 2010;48(3):371–6.
[41] Shaw, David, Martin Phillips, Ron Baker, Eduardo Munoz, Hamood Rehman, Carol Gibson, and C.M., 2012. Final Report on LEAK DETECTION STUDY. , 1201(12).
[42] D. De, Silva, J., Mashford & S., Burn, 2011. Computer Aided Leak Location and Sizing in Pipe Networks Urban Water Security Research Alliance Technical Report No . 17. Urban Water Security Research Alliance Technical Report NO. 17, 2011(17).de. *urban water security research Alliance technical report NO. 17*, 2011(17).
[43] Sousa J, Muranho J, Marques AS, Gomes R. WaterNetGen Helps C-Town. Procedia Eng. 2014;89:103–10, (Available at): http://linkinghub.elsevier.com/retrieve/pii/S1877705814022802.
[44] Starczewska D, Collins R, Boxall J. Transient behavior in complex distribution network: A case study. Procedia Eng. 2014;70:1582–91, (Available at): http://dx.doi.org/10.1016/j.proeng.2014.02.175.
[45] Taylor P, et al. Press. Meas. valve-Induc. transient Flow. Water Pipelines 2015;9006(January):37–41.
[46] Tiselj I, Gale J. Integration of unsteady friction models in pipe flow simulations Intégration des modèles de frottement instationnaires dans les simulations. J. Hydraul. Res. 2010;1686(December):526–35.
[47] Verde C, Visairo N, Gentil S. Two leaks isolation in a pipeline by transient response. Adv. Water Resour. 2007;30(8):1711–21.
[48] Vitkovský, J.P., Simpson, A.R., Lambert, M.F. and Wang, X.J., 2001. An experimental verification of the inverse transient technique for leak detection. In*6th Conference on Hydraulics in Civil Engineering* (pp. 28-30)
[49] Wagner, B.J.M., Shamir, U. & Marks, D.H., 1988. options proposed , a simulation of these options should be done to gain a better understanding of how the proposed alternative systems will be likely to behave under real-life conditions . This paper presents an event-oriented , discrete simulation progra. *Journal of Water Resources Planning and Management, 114(3), 276-294.*, 114(3), pp.276–294.
[50] Walski TM. Technique for Calibrating Network Models. J. Water Resour. Plan. Manag. 1983;109(4):360–72.
[51] Wang, X.J., Lambert, M.F., Simpson, A.R. and Vitkovský, J.P., 2001. LEAK DETECTION IN PIPELINE SYSTEMS AND NETWORKS : A REVIEW. *The Institution of Engineers, Australia Conference on Hydraulics in Civil Engineering Hobart 28 –30 November 2001 LEAK*, (November), pp.1–10.
[52] Wang XJ, Lambert MF, Simpson AR, Liggett JA, Vıtkovský JP. leak detection in pipelines using the damping of fluid transients. ournal Hydraul. Eng. 2002;128(*7*):*697*–711, 128(7), pp.697–711.
[53] Wood DJ, Lingireddy S, Boulos PF, Karney BW, McPherson DL. Numerical methods for modeling transient flow in distribution systems. J. (Am. Water Works Assoc.) 2005:104–15.
[54] Wylie EB, Streeter V. Fluid transients in systems. USA: Englewood Cliffs; New Jersey,; 1993.
[55] Wylie EB, Streeter VL, Suo L. Fluid transients in systems. Englewood Cliffs, NJ: Prentice Hal,; 1993.
[56] Yuan RH, Wan Y, Chen CG. The study of water pipelines leak detection and location technique based on configuration pattern recognition. JOURNAL-GUANGXI UNIVERSITY NATURAL SCIENCE EDITION 2003;28(3):202–5.
[57] Zhang J. Statistical pipeline leak detection for all operating conditions. Pipeline Gas. J. (USA) 2001;299(2):42–5.
[58] J., Zhang, A., Hoffman, K., Murphy, J., Lewis, A. & Twomey, M., 2013. Review of pipeline leak detection technologies. *In Pipeline Simulation Interest Group Annual Meeting*.